(1)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Annual report for work on "Cooled Ion Frequency Standard" ONR Contract - N00014-92-F-0001		5. TYPE OF REPORT & PERIOD COVERED Annual Oct. 1, 1991 - Sept. 31, 1992
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) D.J. Wineland		8. CONTRACT OR GRANT NUMBER(s) ONR Contract No. N00014-92-F-0001
9. PERFORMING ORGANIZATION NAME AND ADDRESS National Institute of Standards and Technology Time and Frequency Division, 847 Boulder, CO 80303		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Physics Program Office, 800 N. Quincy Arlington, VA 22211		12. REPORT DATE 10/22/92
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report)
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release: distribution unlimite

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Atomic spectroscopy; Doppler narrowing; Doppler shifts; frequency standards; high resolution spectroscopy; ion storage; laser spectroscopy; Penning trap; laser cooling

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of this work is to develop techniques to overcome the fundamental limits of present frequency standards--the second order and residual first-order Doppler shifts. To this end we study suitable frequency reference transitions in ions which are stored on electromagnetic traps and cooled by radiation pressure to less than 1K.

Accesion For		
NTIS	CRA&I	☑
DTIC	TAB	☐
Unannounced		☐
Justification		
By		
Distribution /		
Availability Codes		
Dist	Avail and / or Special	
A-1		

Summary of Work on

"COOLED ION FREQUENCY STANDARD"

(FY 92)

submitted to

Office of Naval Research

ONR Contract No. N00014-92-F-0001

Project Leader:

D.J. Wineland

Ion Storage Group

Division 847

National Institute of Standards and Technology

Boulder, Colorado 80303

(303) 497-5286

Contract Description

The purpose of this work is to develop techniques to overcome the fundamental limits of present methods for high resolution spectroscopy and frequency standards--the second order and residual first-order Doppler shifts. To this end, we study suitable frequency reference transitions in ions which are stored in electromagnetic traps and cooled by radiation pressure to < 1K.

Scientific Problem

The scientific problems are (1) to find ways to suppress second order and residual first order Doppler shifts in atomic spectroscopy in a fundamental way--by substantially reducing the kinetic energy of ions stored icn electromagnetic traps, (2) to study suitable reference transitions in ions that can be used as frequency standards, and (3) to study the problems (i.e., systematic effects) generic to all stored ion frequency standards. The goal is to achieve at least a factor of 100 improvement in accuracy over the present best device, the Cesium beam frequency standard, which has an accuracy of approximately 2 parts in 10^{14}.

Scientific and Technical Approach

Laser cooling is employed on all experiments in order to suppress Doppler shifts. We have achieved temperatures as low as 40 μK and temperatures less than 0.1K are routinely achieved. To avoid light shifts on "clock" transitions we investigate "sympathetic cooling" where one ion species is laser cooled and by Coulomb collisions cools another ion species of spectroscopic interest. We continue experiments on Mg^+ and Be^+ in order to study generic problems with traps since these ions are easier to laser cool. We are conducting separate experiments for Hg^+ ions. These experiments have the goal of realizing a frequency standard with 10^{-15} or better accuracy.

I. Two highlights of progress for FY '92.

A. QUANTUM NOISE IN SPECTROSCOPY

IMPORTANCE:

Fundamental: If all sources of "technical noise" in atomic spectroscopy experiments are eliminated, what are the fundamental sources of noise which limit signal-to-noise ratio (S/N)? In experiments where changes in population are detected, the fundamental limiting noise is projection noise. When the atoms are prepared independently (as in optical pumping), $S/N \propto N^{1/2}$ where N is the number of atoms. We have now observed this projection noise on single Hg^+ ions. Through the generation of quantum-mechanically correlated states the S/N can be made to scale as N rather than $N^{1/2}$. We feel this would be a fundamental advance in metrology. To illustrate the potential of the method, consider the following example. If fully correlated states could be obtained, an experiment on 10^{10} correlated atoms would yield the same measurement precision (signal-to-noise ratio) in 1 second as a measurement on 10^{10}

uncorrelated atoms taking 300 years!

Practical: In experiments on stored atomic ions, S/N is limited, in part, by the small number N_i of ions available (S/N $\propto N_i^{1/2}$ for projection noise). The small number of ions available is due to the relatively small densities obtained - caused by mutual Coulomb repulsion of the ions. It is therefore important to achieve the maximum S/N theoretically possible.

ACCOMPLISHMENTS:

Observation of "Projection noise" on single ions. We have detected the 40 GHz ground state hyperfine transition in $^{199}Hg^+$ using Dehmelt's "electron shelving" scheme. Some of the experiments were performed on single ions. By performing the experiment on single ions, or a precisely known number of ions, we can make quantitative comparisons of the observed noise with theory. (In our earlier experiments on $^9Be^+$, the number of ions was constant but not precisely known)

In Fig. 1, we show the S/N observed on a single ion for 29 measurements each at 21 different frequencies near the center of a Rabi resonance for the $^{199}Hg^+$ ground-state microwave "clock" transition.

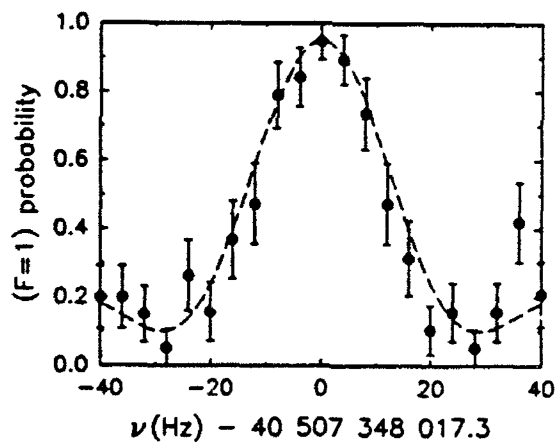

Fig. 1 S/N on $^{199}Hg^+$ Rabi resonance (single ion)

The noise on the side of the Rabi curve is dominated by "projection noise" as evidenced by the fact that the error bars on the side of the Rabi curve are about twice those of the peaks and valleys.

This projection noise arises because, after application of the Rabi resonance fields, the ion is in a superposition of two quantum states (the $^2S_{1/2}(F = 0)$ and $^2S_{1/2}(F = 1)$ ground states). In the detection process, the ion is "projected" into one of these eigenstates. At the half intensity point of the Rabi curve the ion has a 50% chance of being projected into the $^2S_{1/2}(F = 0)$ state. From measurement to measurement, there are fluctuations in this process - sometimes the ion is projected into the $^2S_{½}(F = 0)$ state, sometimes into the $^2S_{½}(F = 1)$ state. These fluctuations are the quantum mechanical "projection noise." We note that this noise could be mimicked by frequency fluctuations in the microwave source which drives the hyperfine transition; we have ruled this out by auxiliary measurements. Also, in these experiments, we still have some sources of technical noise due to background counts and optical pumping effects during state preparation and detection. If these sources of technical noise were absent, the noise on the peaks and valleys would disappear but the noise on the sides of the curve would be only slightly reduced and would be due entirely to projection noise.

Noise reduction using correlated atomic states: The projection noise we have recently observed is the fundamental limiting noise on groups of two-level systems in which the systems are prepared by classical fields (the usual case in optical pumping, for example). Recently, we have investigated for the first time, theoretically, the possibility of reducing the magnitude of the projection noise by using two level systems which are prepared in correlated quantum states. We have been able to show that: (1) certain correlated states do indeed reduce the projection noise and (2) it should be possible experimentally to create the correlated atomic states by parametrically coupling ensembles of two level systems to a quantized oscillator. We hope to realize a demonstration experiment using stored ions. Our preliminary study appears in the paper: "Spin squeezing and reduced quantum noise in spectroscopy," D. J. Wineland, J. J. Bollinger, W. M. Itano, F. L. Moore, and D. J. Heinzen, Phys. Rev. A, to be published.

B. MULTIPOLE EXCITATION OF A BOUND ELECTRON

IMPORTANCE:

Fundamental: High-order multipole transitions are not commonly observed in atomic physics because of their small moments. As a result, studies of high-order nonlinear interactions between atoms and electromagnetic fields have almost exclusively involved electric dipole transitions. A typical example of this case is shown in Fig. 2 where we schematically illustrate one example of harmonic generation (fifth harmonic of ω) where the atom is excited through virtual states (dashed lines) by electric dipole transitions.

By using a single bound electron in a Penning trap as an artificial "geonium" atom (a term coined by Dehmelt), we have experimentally observed a number of degenerate and non-degenerate parametric processes in the limit where multipole interactions dominate the nonlinearity. The process is illustrated schematically (for multipole excitation of order 5) in the inset in Fig. 3.

Practical: Coherent high-order multipole excitation acts as a frequency divider. It appears the processes studied here could eventually be applied to the optical domain where such processes could be useful in frequency metrology.

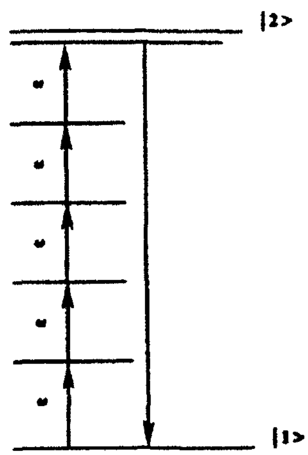

Fig. 2 (harmonic generation)

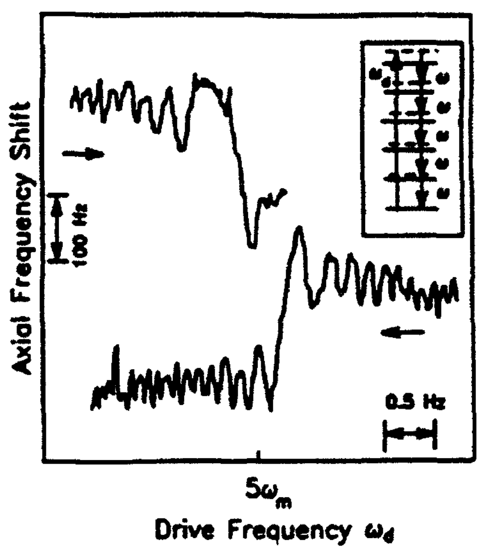

Fig. 3 ($\omega_{drive}/\omega_{response}$ = 5 curve)

ACCOMPLISHMENTS:

High order multipole excitation of an electron bound in a Penning trap.

The motion of a non-relativistic electron in an "ideal" Penning trap has three independent modes: axial motion along the "z" axis of symmetry (frequency ω_z), and the magnetron motion (frequency ω_m) and cyclotron motion (frequency ω_c') in the x-y plane. . For our experiment, typically $\omega_z/2\pi$ = 61.5 MHz, $\omega_m/2\pi$ = 615 kHz, and $\omega_c'/2\pi$ = 3.08 GHz. The response of the axial motion to externally applied time-varying fields was observed by phase sensitively detecting image currents induced in one "endcap" electrode of the trap shown schematically in Fig. 4. We detected the excitation of the cyclotron and magnetron motions to external fields by monitoring the axial motion's frequency. Because of relativistic shifts and non-ideal trapping fields, the axial frequency depended upon the amplitude of the magnetron and cyclotron motions (see e.g.: Robert S. Van Dyck, Jr., Paul B. Schwinberg, and Hans G. Dehmelt, Phys. Rev. D 34, 722 (1986)). We extended this radial detection technique to make it fully phase sensitive by applying two drives and observing the resulting interference beat notes modulating the axial frequency. This gave the relative phases of the different excitations.

The ring electrode of our trap was split into three sectors (Fig. 4). This allowed us to apply a spatially inhomogeneous electric drive field in order to excite the multipole moments of the magnetron and cyclotron motions. The dynamics of these motions can be modelled (classically) by Duffing's equation with a nonlinear force term. Resonance can occur when the drive frequency $\omega_d = (n/m)\omega_j$, with n, m, integers and $\omega_j = \omega_c'$ or ω_m. Subharmonic response, where $\omega_d = n\omega_j$, requires a minimum threshold drive strength before it can occur, and the response will exhibit phase multistability and hysteresis. For our experiment, the nonlinear interaction responsible for the subharmonic response of order n was the excitation of the n'th electric multipole

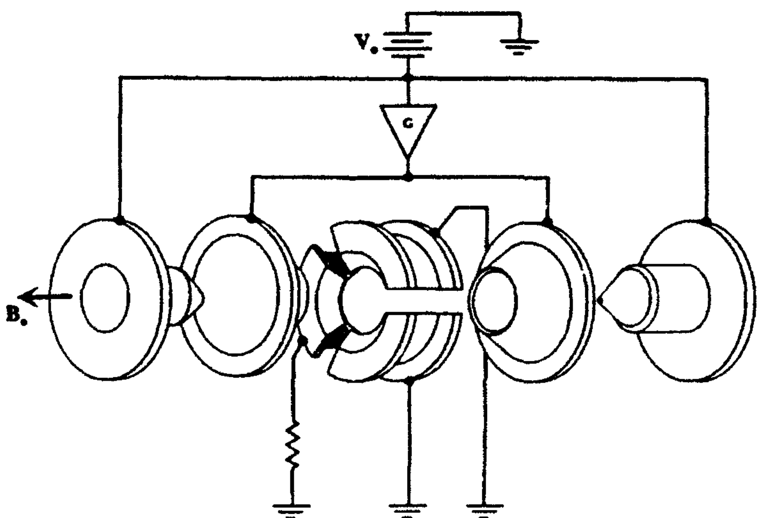

Fig. 4 (Penning trap schematic)

moment of the electron's motion. When two drives are applied with frequencies ω_2 and ω_1, the resonance condition is $n\omega_2 \pm m\omega_1 = p\omega_j$, n, m and p integers. This is an example of stimulated Raman scattering.

In Fig. 3 we show the subharmonic response of order $\omega_{drive}/\omega_{response}$ = 5 of the magnetron motion. Baselines have been offset for clarity and the arrows show the direction of the drive frequency sweep. The overall "step" in the response indicates the shift of the axial frequency caused by the excitation of the magnetron amplitude. Also observed are the beat notes caused by the beats between the magnetron free oscillation and the subharmonically excited oscillation at $\omega_{drive}/5$. The inset shows a quantum representation of this process.

Experimentally we have observed subharmonic response $\omega_d = n\omega_j$ of order n = 1, 2, 3 of the cyclotron motion and n = 1 - 9 of the magnetron motion. In addition, we observed the more general degenerate parametric response $\omega_d = (2/3)\omega_m$. By applying two drive fields, stimulated Raman excitation of the cyclotron motion was observed for $\omega_2 - \omega_1 = \omega_c'$. For the magnetron motion, excitation was observed when $\omega_2 - m\omega_1 = p\omega_m$ with m = 1 and p = 1,2,3, and also when p = 1 and m = 1,2,3. By improving the magnetic field stability it should be possible to observe much higher order nonlinear response.

II. PUBLICATIONS, PRESENTATIONS, ETC.

<u>a. Submitted papers (not yet published)</u>:

1. "Spin squeezing and reduced quantum noise in spectroscopy," D. J. Wineland, J. J. Bollinger, W. M. Itano, F. L. Moore, and D. J. Heinzen, Phys. Rev. A, to be published.
2. "The measurement of Time and Frequency," W. M. Itano and N. F. Ramsey, Sci. Am., submitted.
3. "Quantum Measurements of Trapped Ions," W. M. Itano, J. C. Bergquist, J. J. Bollinger, J. M. Gilligan, D. J. Heinzen, F. L. Moore, M. G. Raizen, and D. J. Wineland, *Proceeding of the International Symposium on Quantum Physics and the Universe*, Waseda Univ., Tokyo, Aug. 19-22, 1992, submitted.
4. "Precise Spectroscopy for Fundamantal Physics," W. M. Itano, J. C. Bergquist, J. J. Bollinger, J. M. Gilligan, D. J. Heinzen, F. L. Moore, M. G. Raizen, and D. J. Wineland, *Proceedings of the IXthe International Conference on Hyperfine Interactions*, Osaka, Japan, Aug. 17-21, 1992. To be published in *Hyperfine Interactions*, submitted.
5. "Quantum projection noise: population fluctuations in 2-level systems," W. M. Itano, J. C. Bergquist, J. J. Bollinger, J. M. Gilligan, D. J. Heinzen, F. L. Moore, M. G. Raizen, and D. J. Wineland, submitted.
6. "High-order multipole excitation of a bound electron," C. S. Weimer, F. L. Moore, and D. J. Wineland, submitted.

<u>b. Papers published in refereed journals</u>:

1. "Ionic crystals in a linear Paul trap," M. G. Raizen, J. M. Gilligan, J. C. Bergquist, W. M. Itano, and D. J. Wineland, Phys. Rev. A<u>45</u>, 6493 (1992).
2. "Sisyphus cooling of a bound atom," D. J. Wineland, J. Dalibard, and C. Cohen-Tannoudji, J. Opt. Soc. Am. <u>B9</u>, 32 (1992).
3. "Linear Trap for High Accuracy Spectroscopy of Stored Ions," M. G. Raizen, J. C. Bergquist, J. M. Gilligan, W. M. Itano, and D. J. Wineland, J. Mod. Optics <u>39</u>, 233 (1992).

c. Books or Chapters submitted:

1. "Recent Experiments on Trapped Ions at the National Institute of Standards and Technology," D. J. Wineland, J. C. Bergquist, J. J. Bollinger, W. M. Itano, F. L. Moore, J. M. Gilligan, M. G. Raizen, D. J. Heinzen, C. S. Weimer, and C. H. Manney, Proc. of the Enrico Fermi Summer School on "Laser manipulation of atoms and ions," July, '91, Varenna, Italy, submitted.
2. "High Resolution Atomic Spectroscopy of Laser-Cooled Ions," D. J. Wineland, J. C. Bergquist, J. J. Bollinger, W. M. Itano, F. L. Moore, J. M. Gilligan, M. G. Raizen, C. S. Weimer, and C. H. Manney, ibid.
3. "Laser Cooling of Trapped Ions," W. M. Itano, J. C. Bergquist, J. J. Bollinger, and D. J. Wineland, ibid.
4. Jim, Varenna one lecture.

d. Books or Chapters published:

1. "Atomic Physics Tests of Nonlinear Quantum Mechanics," J. J. Bollinger, D. J. Heinzen, W. M. Itano, S. L. Gilbert, and D. J. Wineland, Atomic Physics 12, (proc. of the 12th International Conference on Atomic Physics), ed. by Jens C. Zorn and Robert R. Lewis, (Amer. Inst. of Physics press, New York, 1991), p. 461.

e. Number of printed Technical reports and non-refereed papers:

1. "Single Ion Optical Frequency Standard," J. C. Bergquist, W. M. Itano, D. J. Wineland, F. Elsner, and M. G. Raizen, Proc. 45th Symposium on Frequency Control, IEEE Cat. No. 91CH2965-2, (IEEE Publ., New York, 1991) p. 534.
2. "Atomic physics tests of nonlinear quantum mechanics," J. J. Bollinger, D. J. Heinzen, W. M. Itano, S. L. Gilbert, and D. J. Wineland, proc. of the Santa Fe workshop *Foundations of Quantum Mechanics*, ed. by T. D. Black, M. M. Nieto, H. S. Pilloff, M. O. Scully, R. M. Sinclair (World Scientific, Singapore, 1992) p. 40.
3. "Trapped Ions and Laser Cooling III," NIST Technical Note 1353, ed. by J. C. Bergquist, J. J. Bollinger, W. M. Itano, and D. J. Wineland, (U. S. Government Printing Office, Washington, 1992).
4. "Single-ion spectroscopy," J. C. Bergquist, D. J. Wineland, W. M. Itano, F. Diedrich, M. G. Raizen, and F. Elsner, *Optical Methods for Ultrasensitive Detection and Analysis: Techniques and Applications*, B. L. Fearey, Ed., Proc. SPIE 1435, (1991) p. 82.

f. Invited presentations at workshops or Prof. Soc. meetings:

1. Dave Wineland, FACCS conf. on Chemical methods, Anaheim, Oct. '91.
2. Wayne Itano, SE Sect. of APS, Durham, NC, Nov. '91.
3. Wayne Itano, Int. Symp. on Telecommun., Kobe, Japan, Nov. '91.
4. John Bollinger, Tests of QM workshop, UCLA, Nov. '91.

5. Jim Bergquist, 22nd Ann. Winter Colloq. on QE, Snowbird, UT., Jan. '92.
6. Dave Wineland, AAAS meeting, Chicago, Feb. '92.
7. Jon Gilligan, APS Washington meeting, Apr. '92.
8. Jim Bergquist, SFC, May, '92.
9. Jim Bergquist, Varenna summer school, June, '92.
10. Dave Wineland, Crested Butte workshop, Sept. '92, (spin sqz)
11. Wayne Itano, Osaka, Aug. '92 (fund. Phys.)
12. Wayne Itano, Tokyo, Aug. '92 (quant. meas.)

g. Other presentations at workshops or Prof. Soc. meetings:

1. Dave Wineland, DAMOP ann. meeting, Chicago, May '92. (spin sqz.)
2. Carl Weimer, DAMOP ann. meeting, Chicago, May '92. (single e)
3. Fred Moore, DAMOP ann. meeting, Chicago, May '92. (pressure shift)
4. Jon Gilligan, DAMOP ann. meeting, Chicago, May '92. (proj. noise)
5. Jon Gilligan, DAMOP ann. meeting, Chicago, May '92. (Mg^+ g-factor)
6. Fred Moore, Plasma workshop, Irvine, July, '92, (coupled trap)
7. Fred Moore, ICAP, Munich, Aug. '92, (coupled trap)
8. Carl Weimer, ICAP, Munich, Aug. '92, (single e)
9. Dan Heinzen, ICAP, Munich, Aug. '92, (spin sqz)

h. Other invited talks:

1. Wayne Itano, Harvard, Nov. '91.
2. Wayne Itano, U. Mass., nov. '91.
3. Jim Bergquist, NIST, Boulder, colloq., Feb. '92.
4. Dave Wineland, NIST, Gaithersburg, colloq., March. '92.
5. Dave Wineland, IBM, Aug, '92.

i. Honors/awards/prizes/offices etc.

1. Chair, APS Division of Atomic, Molecular, and Optical Physics (DAMOP) (Dave Wineland)
2. Secretary-Treasurer APS Laser Science Topical Group (LSTG) (Wayne Itano)
3. QELS '92 Laser Spectroscopy Chairman (Dave Wineland)
4. Election to National Academy of Sciences (Dave Wineland)